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14. ABSTRACT
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The Importance of Surface Conditions for Spacecraft Charging

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Spacecraft charging is determined by the ambient plasma environment and the surface properties. Whereas the ambient plasma environment is measured in-situ and in real time, the surface property data rely on measurements conducted previously in the laboratory and empirical formulae derived from the laboratory measurements. This note addresses the importance of surface conditions in determining the spacecraft surface potentials. For example, the surface smoothness, thickness, surface composition, and surface contamination are important factors that govern the current balance at equilibrium and the onset of spacecraft charging. These parameters of surface conditions can also greatly influence the accuracy of model calculations of the spacecraft potential. We will provide supporting data to illustrate the main points and to make the case. For spacecraft design, it is inadequate to look up published tables of the coefficients for a given type of surface material. It is necessary to measure the secondary electron coefficient, for example, of an actual piece of the material, because the thickness, smoothness, and surface composition, etc. do matter. In the harsh space environment, surface conditions can also change gradually as a result of the unceasing bombardment by the incoming electrons and ions. All these factors pose uncertainty to spacecraft charging.

Nomenclature

α	=	exponent in the Mott-Smith Langmuir attraction term
BSY	=	backscattered electron yield
δ	=	secondary electron yield (also called secondary electron emission coefficient)
ϕ	=	spacecraft surface potential (V)
δ_{max}	=	maximum value of secondary electron yield
$\Delta\eta$	=	additional term for modifying the BSY formula of Ref.2
E	=	electron energy
E_0	=	parameter specifying the enhancement fall-off rate of η which is material specific.
E_{max}	=	primary electron energy at which the secondary electron yield is maximum
η	=	backscattered electron yield (also called backscattered electron coefficient or reflection electron yield)
eV	=	electron volt
$f(E)$	=	electron velocity distribution expressed in terms of electron energy
$I(\omega)$	=	intensity of incident photons of frequency ω
$J(\omega)$	=	photoelectron flux generated by incident photons of frequency ω on a surface
k	=	Boltzmann's constant
kV	=	kilovolts
m	=	electron mass
n	=	electron density
ω	=	photon frequency
q_e	=	electron charge
q_i	=	ion charge
R	=	surface reflectance

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s	=	parameter of surface condition
SEY	=	secondary electron yield
T*	=	critical electron temperature for the onset of spacecraft charging
T_e	=	electron temperature (eV)
T_i	=	ion temperature (eV)
V	=	volt
Y_{ph}	=	photoelectron yield per incoming electron

I. Introduction

Spacecraft charging to multiple kV (negative volts) may be harmful to the health of onboard electronics. Charging occurs mostly at near geosynchronous orbits during energetic (multiple keV) plasma events. The basic reason for spacecraft charging is the accumulation of electrons on the surface. As an incoming (primary) ambient electron hits a surface with energy E, there is a probability δ(E) of a secondary electron going out. The probability δ(E) is commonly called the secondary electron coefficient or the secondary electron yield (SEY) in the literature. In addition, there is a probability of η(E) backscattered electrons going out. The probability η(E) is commonly called the backscattered electron coefficient, backscattered electron yield (BEY) or simply the reflection coefficient.

Depending on the surface material property and E, δ(E) may exceed unity, meaning "for every electron coming in, there are more than one electron going out". This condition implies charging to positive volts. However, secondary electrons have a few eV in energy and therefore positive charging is up a few volts only. Backscattered electrons are almost as energetic as the primary electrons. However, η(E) is usually very small (<<1) compared with the SEY δ(E).

The onset of spacecraft charging is governed by the balance of the incoming current of primary electrons and the outgoing current of secondary and backscattered electrons. The current balance equation is of the form:

$$\int_0^\infty dE\, E\, f(E) = \int_0^\infty dE\, E\left[\delta(E) + \eta(E)\right] f(E) \tag{1}$$

where f(E) is the electron velocity distribution with $E = (1/2)mv^2$. One can solve eq(1) analytically if one inputs the δ(E), η(E), and f(E) functions. For Maxwellian space plasmas, the f(E) function is of the form:

$$f(E) = n\left(1/2m\pi\right)^{3/2} \exp\left(-E/kT\right) \tag{2}$$

Eq(1) can be written in a more compact way as follows

$$<\delta + \eta> = 1 \tag{3}$$

where

$$< \delta + \eta > = \frac{\int_0^\infty dE\, E\, f(E)[\delta(E) + \eta(E)]}{\int_0^\infty dE\, E\, f(E)} \tag{4}$$

Using the δ(E) formula [1] and the η(E) formula [2] for various materials, one can solve eq(1) or (3) for the critical temperature T*. Below T*, there is no charging; above it, charging occurs. Indeed, the charging data obtained on the Los Alamos National Laboratory (LANL) geosynchronous satellites have repeatedly confirmed the existence of critical temperature for the onset of spacecraft charging [3,4,5]. The observed critical temperature agrees well in order of magnitude with the theoretical values.

As the ambient electron temperature increases beyond T*, the magnitude of the spacecraft potential (negative volts) increases with the temperature. The ambient ions are attracted and collected. As a good approximation, the charging level ϕ is given by the current balance equation:

$$I_e(0)[1 - < \delta + \eta >]\exp\left(-\frac{q_e \phi}{k T_e}\right) - I_i(0)\left[1 - \frac{q_i \phi}{k T_i}\right]^\alpha = 0 \tag{5}$$

where the notations are as in Ref.3. The Mott-Smith and Langmuir [6] orbit-limited ion collection term in eq(5) is applicable in the geosynchronous environment. The power $\alpha = 1$ is for a sphere, ½ for an infinite cylinder, and 0 for a plane. The normalized outgoing electron current is given in eq(4).

In sunlight, the spacecraft surface emits a photoelectron current I_{ph}. For simplicity, no local potential well or differential charging will be considered here. The spacecraft potential is governed by the current balance equation[4]:

$$I_e(0)[1 - < \delta + \eta >]\exp\left(-\frac{q_e \phi}{k T_e}\right) - I_i(0)\left[1 - \frac{q_i \phi}{k T_i}\right]^\alpha - I_{ph} = 0 \tag{6}$$

II. Secondary Electron Yield

As eqs(1-6) indicate above, SEY plays an important role in each aspect of spacecraft charging, viz., onset of spacecraft charging, spacecraft charging voltage in ambient electrons and ions, and spacecraft charging in sunlight. Indeed, good attention has been paid [7] previously to the importance of SEY in spacecraft charging. The Sternglass δ(E) formula [8] and Ref.1 have been used for years in spacecraft charging calculations, eqs(1-6). From time to time, however, there are journal papers reporting on new measurements, or new formulae, of SEY δ(E), each one likely claiming to be better than all previous ones. Which one is really the best? If we know which is the best or most appropriate, we can input it to the above equations for more accurate results.

Figure 1 shows the calculated SEY $\delta(E)$ for gold using some [9-12] of the 'best' formulae published in recent years. The graphs in Figure 1 are similar in the low energy regime below the peak $\delta(E)$, i.e. for primary electron energies $E < E_{max}$. Figure 2 shows the critical temperature T* calculated by using eq(1,3) using some of the 'best' SEY $\delta(E)$ formulae of Figure 1. Similarly, given a SEY $\delta(E)$ formula of choice, one can calculate the spacecraft potential using eqs(5,6). Good inputs generate good outputs. Which one is the best?

III. Effect of Surface Condition on Secondary Electron Yield

The SEY $\delta(E)$ of a surface material is not only a function of primary energy and incident angle but also the surface condition. Surface condition includes the physical features, the chemical composition, the lattice structures, the dose of electrons or ions deposited, the surface temperature, the thickness of layers, etc. Surface smoothness or coarseness affect $\delta(E)$. $\delta(E)$ depends on the incidence angle of the primary electrons. For a coarse surface, the incidence angle varies from one point to another on the surface. For surfaces with grooves, the groove walls can partially re-absorb the secondary electrons emitted from by the depth of the grooves.

In space, prolonged bombardment by energetic ambient electrons or ions may affect the can affect the surface composition and lattice structure near the surface. Protons or ions can cause sputtering, knocking out neutral atoms, although the process of sputtering is usually very slow. Energetic electron penetration into dielectrics can cause build up of significant internal electric fields, depending on the dose and fluence. Energetic protons or ions, because of their large cross-sections and masses compared with electrons, may cause 'knock-on' cascade ionization. In a 'knock-on' event, the target atom recoils, colliding with more atoms in turn.

If the material is very thin, secondary electrons can come out not only from the front side but also from the back side. If the material is composed of a thin layer on top of another material, the primary electrons, passing through the top thin layer with diminished energies, may reach the layer underneath which may have different material properties. The surface temperature effect on SEY has been generally overlooked in the past. It is worthwhile to investigate the temperature effect, especially for very cold temperature situations as we may expect in future explorations of the outer planets.

In LHC (Large Hadron Collider), Switzerland, where the most important and extremely precise (or at least the most expensive) physics experiments will be conducted, serious attention is being paid to the problem of secondary electrons inside the accelerator tubes. There, they have adopted the Furman SEY $\delta(E)$ formula [13], which

features an empirical surface condition parameter s which one can adjust according to the measured secondary electron yield from the actual surface materials. The Furman formula [13] is as follows.

$$\delta(E) = \delta_{max} \frac{s(E/E_{max})}{s-1+(E/E_{max})^{s}} \tag{7}$$

$$E_{max}(\theta) = E_{max}(0)\left[1+0.7(1-\cos\theta)\right] \tag{8}$$

$$\delta_{max}(\theta) = \delta_{max}(0)\exp\left[0.5(1-\cos\theta)\right] \tag{9}$$

IV. Backscattered Electron Yield

For the backscattered electron yield, BEY, the Prokopenko and Laframboise η(E) formula [2] has been used in spacecraft charging, eqs(1-6), for decades. It needs to be updated. The backscattered electron formula of Ref.2 is of the form:

$$\eta(E) = A - B\exp(-CE) \tag{10}$$

where A, B, and C depend on the surface material. The energy integrals in eqs(1,6) are from E=0 to ∞. The ambient electron distribution $f(E)$ is maximum at near E = 0 and decreases to negligibly small values as E increases to about 40 keV. In the limit of E approaching 0, the Prokopenko-Laframboise η(E) formula [2] gives a nearly flat curve and a small finite value (<<1) at E=0.

Recently, Cimino et al [14] and Cimino [15] reported measurements of BEY of copper surfaces for LHC, CERN. Their measurement results showed clearly that the η(E) function of copper rises to unity as the primary electron energy E decreases to 0. Earlier results were obtained by Jablonski and Jiricek [16] using other surface materials. Cimino et al [14] cited that similar results can also be obtained by using quantum mechanical model calculations. Apparently, the property that 'η(0)→1 as E →0' seems general and not for copper surfaces only.

In view of the results of Refs 10-12 and the quantum calculations, Lai and Tautz [17] modified the Prokopenko and Laframboise η formula by adding a term Δη:

$$\eta \rightarrow \eta + \Delta\eta \tag{11}$$

$$\Delta\eta = (1 - A + B)\exp\left(-\frac{E}{E_0}\right) \tag{12}$$

where E_0 = 0.05 keV for gold. The parameters A and B are the same ones appearing in the Prokopenko and Laframboise BSY η (E) formula. The parameter E_0 specifies the enhancement fall-off rate which is material specific. Indeed, the enhanced backscattering formula, eqs(11,12), gives an η value rising to unity at E = 0. Lai and Tautz [17] demonstrated that the added term $\Delta\eta$ affects the value of the anticritical temperature in spacecraft charging.

The value of the parameter E_0 (eq.12) is lacking for other spacecraft surface materials. Similar to our comments in the previous section on SEY, the effects on backscattering due to surface coarseness and contamination need to be understood. For dielectric materials which cannot be grounded, the experimenter must be careful in determining the effect of the negative potential built up as a result of electron bombardments on the material sample. Also, in a very low energy electron beam, electron mutual repulsion due to the beam space charge may be present. These effects may affect the backscattering coefficient, especially at low energies of the incoming electrons.

V. Photoemission

Photoemission from surfaces depends not only on the surface material but also the surface condition. The photoelectron yield $Y_{ph}(R)$ per incoming photon decreases as the reflectance R increases.

$$Y_{ph}(R,\omega) = (1 - R(\omega))Y_{ph}(0,\omega) \tag{13}$$

In the literature, reflectance R is also called reflection coefficient. It is a function of the photon frequency ω. If there is no reflectance (R=0), every incoming photon is absorbed. With a finite R, some photons are reflected, resulting in less energy transfer from the incident light to the surface material. The photoelectron flux $J(R)$ generated from a surface is given by

$$J(R,\omega) = J(0,\omega)\big(1 - R(\omega)\big) = I(\omega)Y_{ph}(R(\omega)) \tag{14}$$

where

$$J(0,\omega) = I(\omega)Y_{ph}(0,\omega) \tag{15}$$

In eqs(14,15), $I(\omega)$ is the incident light intensity which is a function of the light frequency ω or quantum energy $h\omega$. For sunlight at geosynchronous altitudes in the magnetosphere, the most important solar spectral line is the Lyman Alpha, which has about 10 eV in energy.

Depending on the reflectance R, the photoelectron yield $Y_{ph}(R,\omega)$ and therefore the photoelectron current I_{ph}, varies. Varying the photoelectron current I_{ph}, the spacecraft charging calculations, eq(1-6), would be affected accordingly [Fig 6].

A highly reflective surface ($R \rightarrow 1$) generates little or no photoemission ($J(R) \rightarrow 0$, eq(14)). For spacecraft charging calculations, it is insufficient to use a value for the photoelectron yield Y_{ph} of a given surface material. It is necessary to specify the surface condition, especially the reflectance.

As an example of the reflectance effect, let us consider a mirror in space. If a highly reflective surface is located next to a non-reflective one, the difference in their photoemissions renders differential charging between the surfaces in sunlight [18]. In turn, differential charging may cause a sudden discharge, which may cause satellite anomalies or failures. Highly reflective mirrors have been used for concentrating sunlight onto solar cells on satellites such as Telesat Anik F1, Telesat Anik F2, and PamAmSat's Galaxy 11 [http://sat-index.com/failures/702arrays.html].

We should also mention that surfaces with deep grooves emit less photoelectrons than smooth surfaces. Though the incident photons may be well absorbed by the material, the photoelectrons generated from the deep grooves may be re-absorbed by the walls of the grooves.

VI. Conclusion

In spacecraft charging calculations, secondary and backscattered electron emissions are centrally important. They control the critical temperature T*, which is ambient electron temperature at which the onset of spacecraft charging occurs. They also control the spacecraft charging voltage, which is given by the balance of all incoming and outgoing currents. It has been customary to use a value of SEY $\delta(E)$ and a value of BSY $\eta(E)$ for a given surface material. It is insufficient to use the 'best' values of $\delta(E)$ and $\eta(E)$ published in the literature. It is necessary to specify the surface condition. Similarly, spacecraft charging in sunlight requires the knowledge of the photoelectron yield $Y(\omega)$ for a given surface material. Again, it is necessary to specify the surface condition, especially the reflectance.

Perhaps it should be mentioned that a surface with deep groves emits less secondary, backscattered, and photoemission electrons. This is because such low energy electrons liberated from the depth of a groove are likely to be re-absorbed by the groove walls.

In conclusion, for spacecraft engineering, it is advisable to measure the $\delta(E)$, $\eta(E)$, and $Y_{ph}(\omega)$ yields from the actual pieces of surfaces before assembly. Care should be taken to preserve the surface condition, such as smoothness, cleanliness, and surface temperature, so that the yield functions in space will remain almost the same as measured in the laboratory.

However, if the yield functions change slowly in the hazardous space environment because of bombardments by energetic electrons and protons, all careful measurements before launch would be in vain. In-situ monitoring of the yield functions would be helpful but perhaps it is not practical at present.

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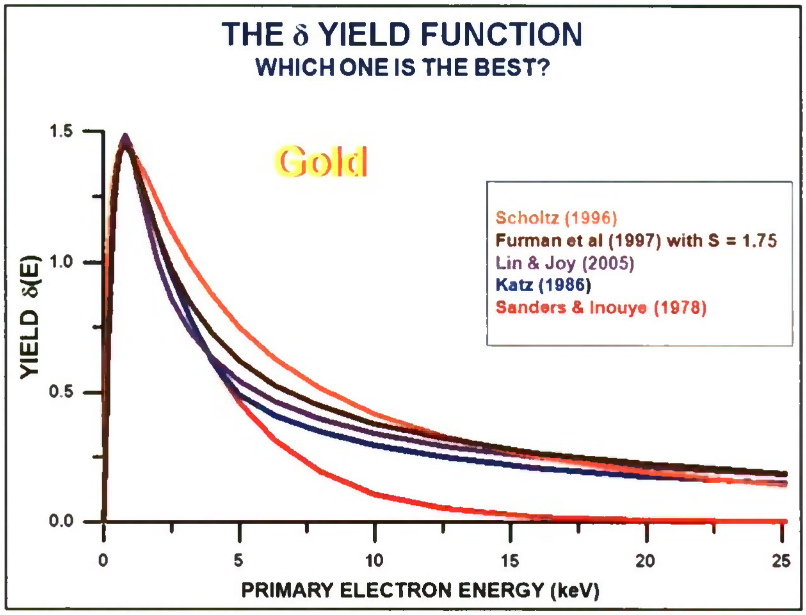

Fig.1 Some of the 'best' secondary electron yield δ(E) functions [9-12] obtained in recent years. There is little or no difference at energies E below the maximum of δ(E). Above it, all are different. What one is the best?

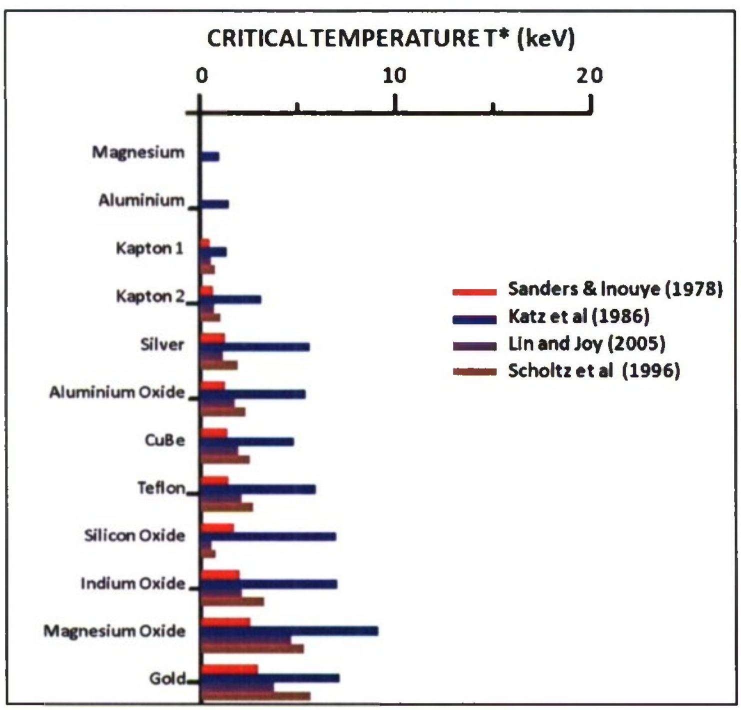

Fig.2 Critical temperature for the onset of spacecraft charging calculated by using various 'best' δ functions.

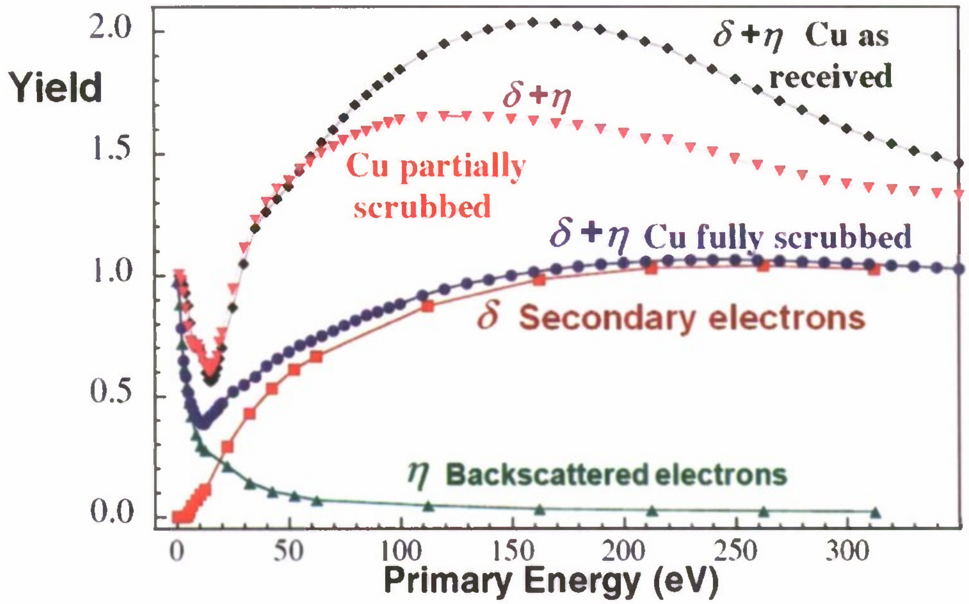

Fig.3 The Cimino et al [15] measurements of SEY δ(E) of copper. The value of δ(E) varies significantly depending on the surface condition. At very low energies, the backscattering electron yield BSE η(E) clearly dominates over the secondary electron yield. [From Ref.15, Courtesy Cimno]

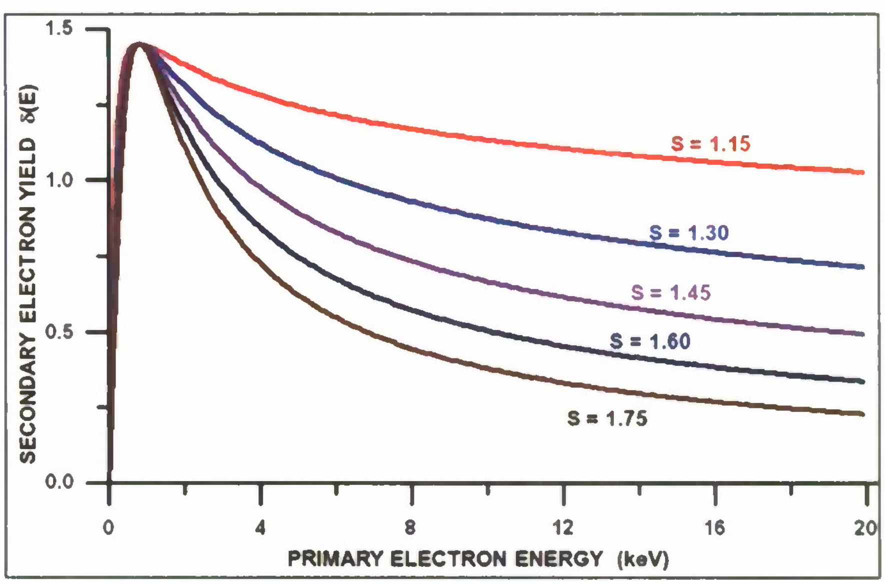

Fig.4 SEY δ(E) calculated by using Furman's formula [13]. The empirical parameter *s* characterizes the condition of a given surface material.

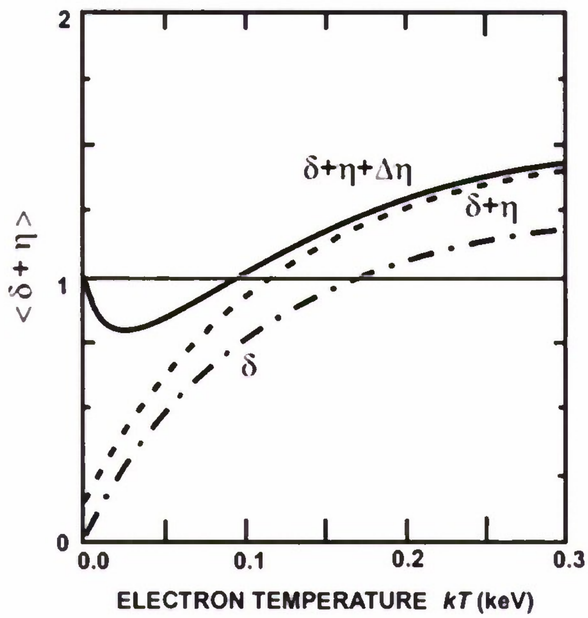

Fig.5 Current balance equation $<\delta+\eta>=1$ for the anticritical temperature with and without enhanced scatter for the surface material gold. We have used E_0 = 0.05 keV for the enhancement fall-off parameter. [From Ref.18, Courtesy Lai].

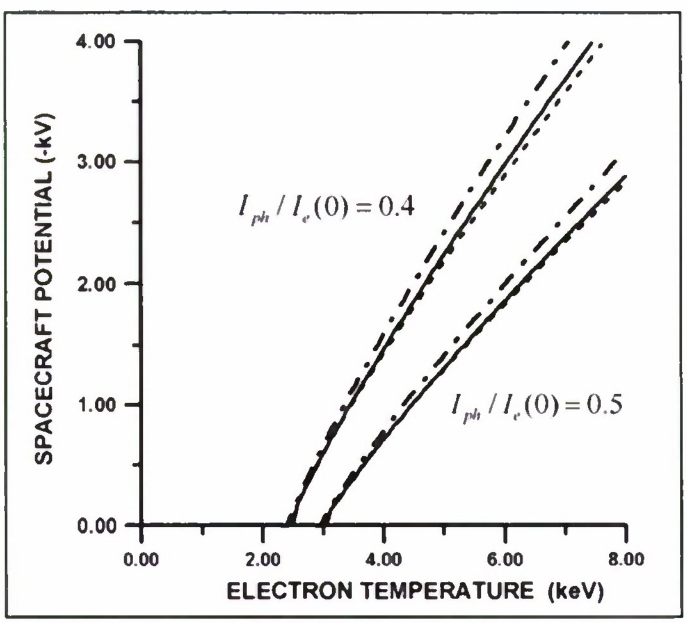

Fig.6 Calculated surface potentials of aluminium oxide in 1-D, 2-D, and 3-D with $I_{ph}(0)$= 0.4x$I_e(0)$ and 0.5x$I_e(0)$. Dot-dash-dot is for 1-D, solid is for 2-D, and dash for 3-D. [From Ref.4, Courtesy Lai]